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SLP-2D: A new Lagrangian particle model to simulate pollutant dispersion in street canyons

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Abstract

In this paper, pollutant dispersion inside a street canyon is simulated using SLP-2D (street Lagrangian particles). SLP-2D is a Lagrangian particle model developed by Research Center for Energy, Environment and Technology (CIEMAT), and it uses wind flow data provided by FLUENT CFD simulations to compute particle trajectories. The simulations presented are divided into two parts. In the first part Meroney, et al. [1996. Study of line source characteristics for 2-D physical modeling of pollutant dispersion in street canopies. Journal of Wind Engineering and Industrial Aerodynamics 62, 37–56] wind tunnel experiment is analyzed and we find good agreement between computed and experimental results. In the second part, dispersion inside real street canyons from Stockholm (Hornsgatan Street) and Berlin (Frankfurter Alee) is studied. Field data have been provided by street emission ceilings (SEC) team for use in SEC intercomparison model exercise.

Keywords: Street canyon; Lagrangian particle model; CFD; RANS simulations

1. Introduction

In recent years, traffic emissions inside streets produce high levels of pollution and an important problem related to urban air quality in many cities. To analyse this problem, a large amount of investigations has been carried out. Field measurements (Vachon et al., 2000), wind tunnel experiments (Meroney et al., 1996 or Kastner-Klein and Plate, 1999) and numerical simulations (Sini et al., 1996 or Assimakopoulos et al., 2003) are performed in different configurations of street canyons.

One way to calculate air pollutant concentration is to couple a flow model as Computational Fluid Dynamics (CFDs) with a Lagrangian particle model (Borrego et al., 2003). Lagrangian particle models calculate pollutant concentration by means of a large number of particles released in atmospheric flow. Each particle follows an independent trajectory each time step, its motion is described by a deterministic component obtained of the wind field and a stochastic component related to the local turbulence. This type of models has been already used for micro scale or street canyon dispersion (Lee and Näslund, 1998; Leuzzi and Monti, 1998; Xia and Leung, 2001a; Borrego et al., 2003).

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The aim of this paper is to evaluate the performance of the Lagrangian particle model in two dimensions developed by CIEMAT (SLP-2D). Two different types of validation exercises have been carried out simulating a wind tunnel experiment (Meroney et al., 1996) and real street canyons (Hornsgatan Street from Stockholm and Frankfurter Alee from Berlin). Turbulence produced by traffic has been taken into account to simulate pollutant dispersion in real street canyons. In addition, deposition processes have also been considered. The objective of the wind tunnel case simulation is to assess the performance of the model in less complex situation with more controlled conditions. However, real street canyon simulations are needed to verify the turbulence produced by traffic and deposition modules.

2. Methodology

SLP-2D (street Lagrangian particles) is a Lagrangian particle model in two dimensions developed by Research Center for Energy, Environment and Technology (CIEMAT). Pollution is simulated by means of a large number of particles released in atmospheric flow and traffic emissions are employed to assign mass corresponding to each particle. Particles are moved each time step by a deterministic term obtained of wind flow ($\bar{u}$) and a stochastic term related to local turbulence (u'). Therefore, the expressions used to calculate particle displacements are the following:

$$u = \bar{u} + u', \tag{1}$$

$$x(t + \Delta t) = x(t) + \Delta t(\bar{u}(t) + u'(t)). \tag{2}$$

The main difficulty of these models is in calculating stochastic component. u' is computed assuming that its values is a combination of two terms. One of them is related to u' value of the same particle in the previous time step and the second term (u'') is a purely random velocity (Zannetti, 1990)

$$u'(t + \Delta t) = R(\Delta t)u'(t) + u'', \tag{3}$$

where $R(\Delta t)$ is a vector containing autocorrelations and the term $R(\Delta t)u'(t)$ denotes the effect of velocity at time t fluctuation on fluctuation velocity in the next time step $t+\Delta t$. u'' is calculated assuming that it is a random vector whose components are normally distributed with mean zero and that standard deviations involved can be expressed to satisfy $\sigma_{u''} = \sigma_{u'}(1 - R^2(\Delta t))^{1/2}$ (Zannetti, 1990; Xia and Leung, 2001a).

$\sigma_{u'}$ is the standard deviations of components of u' and it is computed using turbulent kinetic energy (k) field provided by CFD software. It is assumed that $\sigma_{u'}$ is proportional to $k^{1/2}$. The CFD simulations are based on RANS equations with RNG k–ε turbulence model. Therefore, the outputs of CFD model related to turbulence are turbulent kinetic energy (k) and its dissipation rate (ε), but the standard deviations of components u' ($\sigma_{u'}$) are necessary for the Lagrangian particle model (SLP). Hence, k is used for computing $\sigma_{u'}$. k is defined by $k = 0.5(u'^2 + v'^2 + w'^2)$ in 3-D and by $k = 0.5(u'^2 + w'^2)$ in 2-D. We assume that $u'^2 = w'^2$ and then $u' = k^{0.5}$ in 2-D (cases studied in the paper). Therefore, in the cases studied in this paper, the proportionality constant is 1. Other proportionality constants were tested for the case of Meroney experiment but the results were not improved.

The general form of $R(\Delta t)$ (Hanna, 1982) is expressed as an exponential function depending on time step and Lagrangian time scale, $R(\Delta t) = \exp(-\Delta t/T_L)$. However, we used the relationship proposed of Uliasz (1994) and Xia and Leung (2001a) between Δt and T_L ($\Delta t = 0.1 T_L$). However, the Lagrangian time scale is introduced in the simulations by the selection of the time step. Actually, there are many different T_L due to the inhomogeneities within the flow, but these have been lumped together into just one. Therefore, in these cases where we use a constant value of Δt, we have a constant value of R. However, the time step has to be chosen. Δt is related to the characteristics of the scenario analysed and we propose to use in these cases $\Delta t = F \times H_0/U_0$ ($T_L = 10F \times H_0/U_0$), where H_0 is the characteristic length (the height of obstacles), U_0 is the characteristic velocity and F is a constant. A sound estimate of F can be 1/10 ($\Delta t = 1/10 \times H_0/U_0$ and $T_L = H_0/U_0$), but for these simulations, different values of F have been proved ranging between 1/5 and 1/30. For example, for the Meroney case, we use $\Delta t = 1/30 \times H_0/U_0$. For all field cases, we use a constant value ($\Delta t = 1$ s), then F to each velocity ranges between 1/5 and 1/30 in all cases. The optimum value of this factor used is not constant for each case. This can be related to the fact that the Lagrangian time scale is not really constant. However, the use of different F within this range does not produce large changes in the results.

Rigorously, some equations of this Lagrangian particle model can only be applied to stationary,